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OPTIMAL AIRFIELD CAPACITY EXPANSION

by

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The US Air Force recently developed the Global Reach Laydown Package (GRLP) concept for expanding the capacity of overseas airfields available for its use during a military operation. The GRLP concept consists of five force modules that can be rapidly deployed to temporarily expand capacities of overseas airfields. These force modules contain personnel and equipment necessary for increasing airfield capacity.

To aid in the decision to deploy these modules, this thesis develops integer programming models. These models produce deployment schedules for modules that minimize the weighted combination of capacity shortfalls and the cost of transporting modules to their destinations. Also included is the option to redeploy modules after their initial placement. To illustrate their use, these models were implemented in the General Algebraic Modeling System (GAMS) using a sample problem data. Several issues of interest in planning module deployment are also discussed.

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OPTIMAL AIRFIELD CAPACITY EXPANSION

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The US Air Force recently developed the Global Reach Laydown Package (GRLP) concept for expanding the capacity of overseas airfields available for its use during a military operation. The GRLP concept consists of five force modules that can be rapidly deployed to temporarily expand capacities of overseas airfields. These modules contain personnel and equipment necessary for increasing airfield capacity.

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THESIS DISCLAIMER

The reader is cautioned that the computer program developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the functions are free of computational and logical errors, they cannot be considered fully verified or validated. Any application of these functions without additional verification and validation of the code is at the risk of the user.

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EXECUTIVE SUMMARY

Realignment of the US military's force structure has decreased the number of overseas airfields available for use in airlift operations. Without adequate number of airfields that have sufficient capacity, troops and materiel can not be delivered to the right place at the right time. To effectively support a wide range of contingency operations, the US Air Force's Air Mobility Command (AMC) must have the ability to rapidly expand the capacities of the remaining overseas airfields. Instead of permanently increasing airfield capacity, AMC developed the Global Reach Laydown Package (GRLP) concept, consisting of five air deployable force modules. These force modules contain personnel and equipment necessary to provide additional infrastructure to an airfield, thereby increasing its capacity. The key advantage of the GRLP concept is that the modules can be airlifted and deployed at overseas airfields in at most five days. However, the force modules must be deployed at the appropriate airfields and time in order to use them most effectively.

The goal of this thesis is to aid airlift planners in determining the most effective placement of these modules in support of an airlift operation. In particular, the decision of where and when to place these modules is formulated as integer programming problems, also known as Throughput Capacity Expansion problems. There are two options in placing the modules. One allows modules to be redeployed to different airfields after their initial placement and the other does not. As an objective, problems under both options minimize the weighted sum of the total amount of capacity shortfalls and the transportation cost associated with deploying force modules.

When implemented in the General Algebraic Modeling System (GAMS), solutions to the TCE problems specify schedules for deploying/redeploying force modules at various airfields. Moreover, as an aid to decision making, these solutions can be analyzed and provide useful information. Based on a sample problem data, the analysis shows that (i) the trade-off between availability of lift assets and shortfalls can be quantified, (ii) the marginal decrease in shortfalls from having three or more packages of force modules is negligible, and (iii) shortfall is unaffected by airfield/module compatibility if more than 50% of the airfield-module pairs are compatible.

I. INTRODUCTION

The current downsizing and realignment of the US military's force structure have reduced the number of troops permanently stationed overseas. When responding to crises, this reduction means that the bulk of combat and support forces must come from bases in the continental US (CONUS). On the other hand, the US must be able to rapidly deploy its forces in order to respond swiftly to national security threats and deter potential aggressors. To deploy and sustain forces overseas, the US depends on three mobility elements: sealift, airlift and prepositioned materiel. Being the faster of the two lift elements, this thesis focuses on airlift which carries personnel and limited amounts of high priority equipment and supplies.

Effective and efficient airlift operations depend on aircraft and airfield availability. Without sufficient number of aircraft and adequate number of airfields with proper capacities, troops and materiel can not be delivered to the right place at the right time. As the number of overseas airfields continues to decrease, capacities of the remaining ones must be increased in order to maintain sufficient capacity to support airlift operations. Instead of permanently increasing the capacities of the remaining overseas airfields, the US Air Force developed the Global Reach Laydown Package (GRLP) concept consisting of five *force* modules. These force modules contain personnel and equipment necessary to provide additional infrastructure to an airfield, thereby increasing its capacity. The key advantage of the GRLP concept is that the modules can

be airlifted and deployed at overseas airfields in at most five days. However, the force modules must be deployed at the appropriate airfields and time in order to utilize them most effectively.

A. PROBLEM STATEMENT

Given a set of available force modules, the problem is to determine when and where to place them in order to maximize their utility. One method of addressing this problem is to formulate it as an optimization model that places force modules at airfields in order to minimize shortages of airfield capacity. To make this problem meaningful, equipment and supplies are assumed to be delivered to airfields by the specified time. When viewed as a tool, the amount of shortage produced by the model provides one measure of feasibility and is useful in planning airlift operations.

B. THESIS ORGANIZATION

Chapter II provides a detailed discussion of airfield capacity expansion, including a description of the Global Reach Laydown Package concept. Mathematical programming formulations of the problem are presented in Chapters III and IV. The implementation and applications of these formulations are presented in Chapter V where an example problem is solved using unclassified data. Conclusions are presented in Chapter VI.

II. AIRFIELD CAPACITY EXPANSION

The success of any combat operation depends on rapid closure of the personnel, equipment and supplies required to execute the operational plan. Delays in the delivery of men and materiel increase the vulnerability of combat forces already in the crisis area and may result in unnecessary loss of lives. Planning an effective airlift operation requires determining whether there is sufficient airfield capacity to sustain the level of cargo movement needed to satisfy the combat operation's closure requirements. If airfield capacity is inadequate, then the airlift operation cannot delivery the necessary amount of cargo and personnel in time, regardless of the amount of airlift aircraft that are available.

The remainder of this chapter describes how the closure requirements for a combat operation are converted to airlift movement requirements, discusses what constitutes "sufficient" airfield capacity and presents how the GRLP concept can be utilized to expand airfields whose capacities are inadequate.

A. MOVEMENT REQUIREMENTS

A combat operation's closure requirements are determined by the operational plan. Execution of the plan depends on the correct combat and support forces being in the right place at the right time with all of their essential equipment and supplies. Once the required combat forces are identified and the date when they are needed in-theater to support the operational plan is determined, a *movement requirement* for the each force's

equipment and personnel is generated. A movement requirement specifies an amount of cargo and personnel to be moved, an origin airfield (Aerial Port of Embarkation or APOE), a destination airfield (Aerial Port of Debarkation or APOD), a load date, and a delivery date. In this thesis, personnel movement will not be considered and henceforth, a movement requirement will refer only to cargo.

The load date or the Available to Load Date (ALD) is the day that the cargo can be loaded on an aircraft at the APOE . There are typically three delivery dates specified for a given movement requirement: Earliest Arrival Date (EAD), Latest Arrival Date (LAD), and Required Delivery Date (RDD). The EAD is the earliest date that the cargo can be accepted at the APOD, the LAD is the latest date that the cargo can arrive at the APOD and still support the operation, and the RDD is the target date that the cargo should arrive at its destination and complete offloading [Ref 1]. Although any date within the limits of the above specified dates can be used in planning the operation, this thesis uses for illustration ALD for loading and RDD for unloading cargo at airfields. Moreover, in planning the capacity expansion, cargo scheduled for the same ALD or RDD are assumed to be loaded and unloaded in one day. This is the worst case scenario. If all cargo can be delivered on time under this assumption, then they are also on time when the loading or unloading is spread out over several days.

Once all movement requirements have been defined and the load and delivery dates determined as discussed above, it is possible to calculate the daily amount of cargo, measured in short tons (STONS), that is planned to depart an APOE or arrive at an

APOD during the planning period. For each airfield, this amount can be viewed as the minimum level of airfield capacity necessary to ensure that all movement requirements for a given day can be loaded or unloaded at the airfield, i.e., the airfield's *required capacity* for that day. Graphing an airfield's required capacity for each day in the planning period generates a *required capacity profile*. This profile represents the level of airfield capacity needed to satisfy the operation's closure requirements over the entire planning period. Figure 1 shows an example of a required capacity profile for a fictitious airfield over a period of nine days. To examine whether the existing capacity at an airfield is sufficient to support the operation, the airfield's *throughput capacity* must be determined and compared to the required capacity profile.

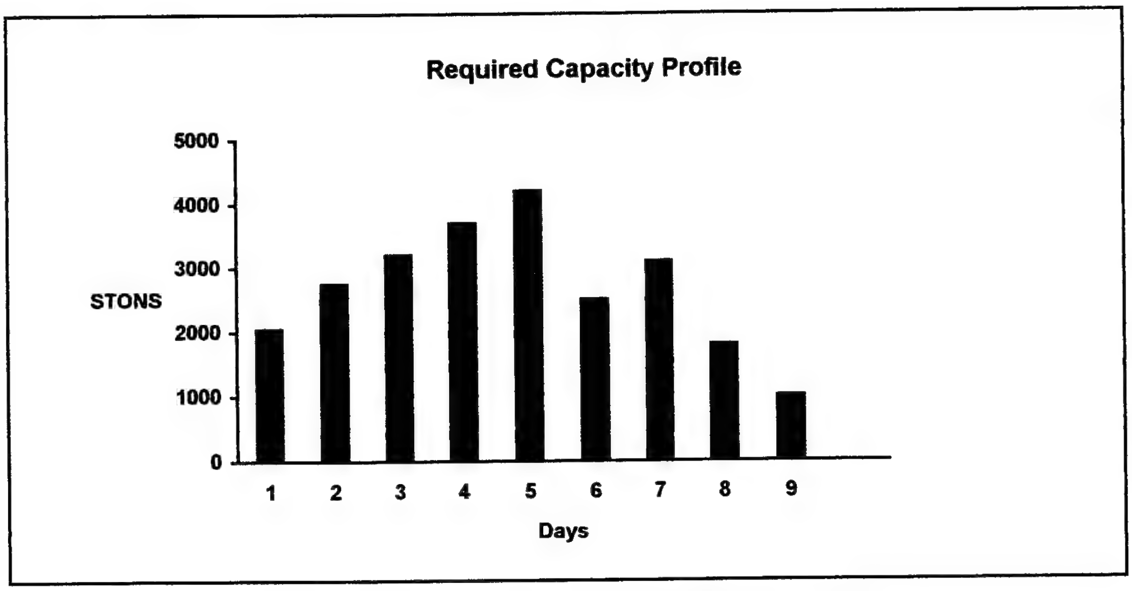

Figure 1: Required Capacity Profile Example

B. AIRFIELD THROUGHPUT CAPACITY

Throughput capacity is defined as the daily amount (in STONS) of cargo that can be loaded and offloaded at an APOE and APOD, respectively. The Air Force [Ref 2] quantifies an airfield's throughput capacity in the term Maximum on Ground (MOG) value. A MOG value is the number of aircraft, of a specific type, that can be simultaneously serviced within that aircraft's planned ground time.

Many factors, such as the amount of available ground support equipment, material handling equipment, and parking space (ramp space), determine the MOG value for an airfield. Wide-bodied aircraft, such as the C-5, consume more parking space and support equipment than do narrow-bodied airframes like the C-141. So, if an airfield is to service only one type of aircraft, the MOG value for C-5s would be smaller than that for C-141s. In essence, an airfield has only one MOG value, but it can be expressed with different units of measurement, i.e., MOG = 4 *C-5s* or MOG = 6 *C-141s*. For planning purposes, dealing with dissimilar units is cumbersome. Previous studies (see, e.g., Ref 3) convert MOG values in different units to a value based on the number of narrow-bodied equivalent (NBE) aircraft. For example, if one C-5 is equivalent to 1.5 NBE MOG, then 3 C-5s are the same as 4.5 NBE MOG and 3 C-5s and 2 C-141s are the same as 6.5 NBE MOG.

To compare an airfield's required capacity profile and its throughput capacity, it is necessary to convert the NBE MOG value to STONS of cargo per day. Given the planned ground time and maximum payload of a NBE aircraft, throughput capacity in

STONS / day can be calculated from a NBE MOG value. For example, consider an airfield with a NBE MOG value of 10. If the planned ground time for each aircraft is 3 hours and the maximum payload equals 30 STONS, the throughput capacity is 2400 STONS / day, i.e., (10 NBE aircraft / 3 hours) x (24 hours / day) x (30 STONS / NBE aircraft) = 2400 STONS / day [Ref 3: p.23].

When an airfield's required capacity for a given day is greater than its throughput capacity, a *capacity shortfall* exists. Figure 2 below shows that there is a shortfall of 1000 STONS on day 5. Summing the daily capacity shortfalls over the entire length of an

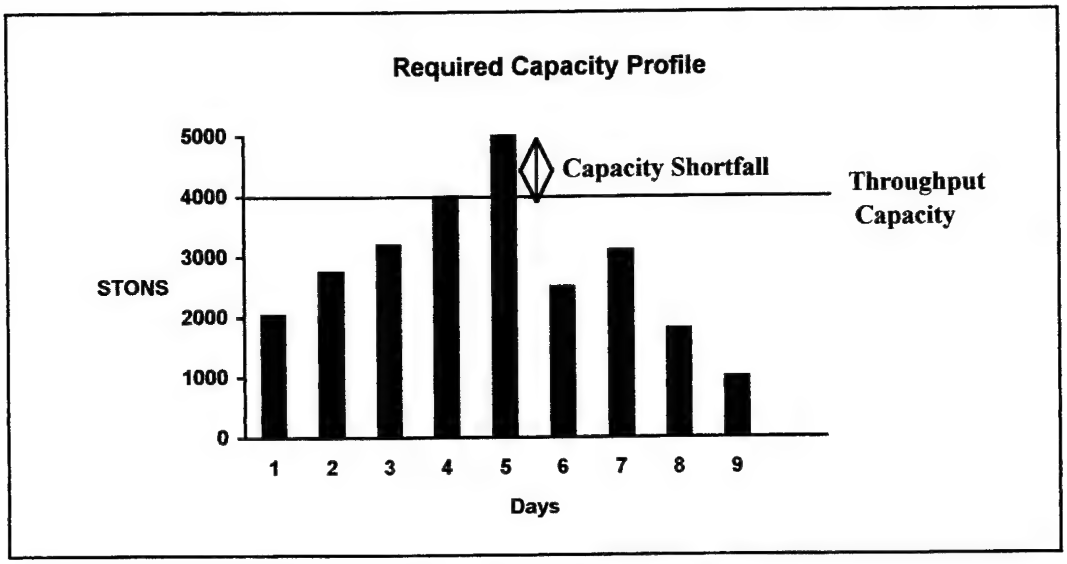

Figure 2: Throughput Capacity Shortfalls

airlift operation provides a measure of its feasibility. If the sum is zero, then there is sufficient airfield capacity for all movement requirements to be delivered on time. When the sum is greater than zero, then existing capacity is insufficient and the sum indicates the amount that is lacking. To supplement existing airfields with additional capacity, the

US Air Force (USAF) developed the Global Reach Laydown Package concept which is described next.

C. GLOBAL REACH LAYDOWN PACKAGE CONCEPT

The mission of the USAF's Air Mobility Command (AMC) is to provide a robust airlift capability that ensures "rapid response to a wide spectrum of contingencies, ranging from humanitarian lift operations to two major regional contingencies." [Ref 4: p. 3-17] In 1992, Operation Restore Hope in Somalia further demonstrated that AMC must have the ability to conduct airlift operations in austere environments. To maintain the flexibility necessary to support military operations anywhere in the world, AMC identified the need for a system of mobile infrastructure that can be rapidly deployed to establish effective airlift operations at airfields where infrastructure is limited or nonexistent [Ref 5]. This need led to the development of the Global Reach Laydown Package concept.

As stated in the introduction, the GRLP concept consists of five force modules. These modules contain equipment and personnel necessary to establish airlift operations at airfields where no infrastructure exists [Ref 5]. Typically, a module includes personnel and equipment for services such as fueling, fire fighting, ground transportation, cargo handling, maintenance, weather forecasting, communications, and air traffic control. Ref. 5 describes the force modules as follows:

1. **Onload**. The Onload module is designed for an airfield (Aerial Ports of Embarkation or APOEs) where the primary operation is onloading cargo for delivery to intheater airfields. These APOEs are normally CONUS bases.
2. **Stage**. The Stage module is primarily designed to handle crew rest and crew changes, but it does possess limited cargo throughput capacity.
3. **Hub**. The Hub module is designed for the principle in-theater delivery locations (Aerial Ports of Debarkation or APODs).
4. **Spoke**. The Spoke module is designed for smaller airfields that are typically endpoints for delivery of cargo to the user.
5. **Contingency Tanker Task Force** (CTTF). The CTTF module is designed to provide tanker aircraft and the related support equipment needed to establish aerial refueling operations.

For the first four modules, Table 1 lists the number of personnel, amount of equipment, and additional throughput capacity reported in Ref. 6. The last module, CTTF, does not increase throughput capacity and will not be considered henceforth.

Module Type	Module Composition		Module Throughput Capacity
	Personnel	Equipment	
Onload	187	217 STONS	200 STONS/Day
Stage	649	962 STONS	99 STONS/Day
Hub	1457	1942 STONS	500 STONS/Day
Spoke	234	509 STONS	60 STONS/Day

Table 1: Composition of Force Modules

D. PLACEMENT OF FORCE MODULES

Proper placement of these four force modules can alleviate throughput capacity shortfalls by increasing an airfield's existing throughput capacity. To determine the most effective placement, three decisions must be made: (1) which airfields should be expanded, (2) when should they be expanded and (3) by how much should they be expanded. One possible solution would be to deploy enough modules to each airfield in the beginning of an airlift operation so that its expanded throughput capacity is equal to or greater than its maximum required capacity for the planning period. This would ensure that there are no throughput capacity shortfalls. However, there are a number of reasons why this solution is not realistic. First, there are only a limited number of force modules available for use. Specifically, the Air Force has identified sufficient equipment for only two modules of each type [Ref 4: p. 3-18]. Second, since the composition of the four modules are similar, placing more than one module at an airfield results in significant duplication of equipment and personnel. Thus, the additional throughput capacity gained by the airfield would not necessarily equal the sum of the individual modules' throughput capacities. Finally, aircraft available for transporting supplies and equipment are limited. If too may aircraft are used to deploy force modules on a given day, there may not be enough aircraft left to transport the movement requirements.

There are also two placement options: one with the possibility of redeployment and the other without. Without redeployment, each force module may be placed at only one airfield and it remains there for the entire airlift operation. The redeployment option

allows the force modules to be moved to a different airfield after their initial placement. Each placement option has its pros and cons. The option without redeployment uses fewer aircraft so that more are available for transporting cargo. On the other hand, the redeployment option is more flexible, for the module placement can be adjusted to better suit throughput shortfalls that vary with time. The next chapter describes a problem that is used to determine the optimal placement of the GRLP force modules.

III. THROUGHPUT CAPACITY EXPANSION PROBLEM

As discussed in Chapter II, the main criteria for determining where and when to place GRLP force modules is to minimize the total amount of throughput capacity shortfalls that occur during an airlift operation. However, there are other issues to consider, such as the number of airlift assets used to deploy the modules themselves. In an airlift operation, the number of available aircraft is limited. So, if more aircraft are used to deploy the modules, less are available for delivering cargo. However, more modules generally means more throughput capacity which leads to a greater reduction in shortfalls. Therefore, it would be inappropriate to consider minimizing shortfalls without addressing the expense or cost of transporting the modules for placement. The Throughput Capacity Expansion (TCE) problem addressed in this chapter considers both the shortfalls and transportation cost in the objective function.

This chapter consists of three sections. The first section states problem assumptions. The second presents the mathematical formulation of the TCE problem under the assumption that redeployment is allowed. The TCE problem without redeployment is discussed in the following chapter. Finally, the third section discusses related research.

A. EXPANDING AIRFIELD THROUGHPUT CAPACITY

The mathematical programming formulation of the TCE problem presented below assumes the following:

1. To keep the size of the problem manageable, modules are deployed to airfields only on the first day of each week. Since travel time is relatively short, modules generally arrive at airfields on the same day they are deployed. In this thesis, the terms "deployed" and "placed" are, therefore, interchangeable.
2. To account for transportation and setup delay, a module becomes operational k days after deployment. Depending on the scenario, k is between three and five days. For example, if an Onload module is deployed to an airfield on day 8, then the airfield will not have the additional 200 STONS daily throughput capacity provided by the module until day $(8 + k)$.
3. Capacity shortfalls are calculated on a daily basis.
4. On any particular day, at most one module can be in place at an airfield.
5. The cost of transporting a module to an airfield is the total amount of cargo in the module's composition. This measure of transportation cost is appealing since its units are in STONS, the same as the measure for the amount of shortfalls.

Under these assumptions, the TCE problem can be stated as follows. Given the daily required capacities and original throughput capacity for each airfield, find the optimal deployment schedule for the modules that minimizes the weighted sum of the

total amount of throughput capacity shortfalls and the cost of transporting modules to airfields.

B. MATHEMATICAL FORMULATION

A mathematical formulation of the TCE problem with redeployment is given below.

Indices:

a	Airfields utilized in the mobility operation
p	Module type
t	time period in days
w	time period in weeks

Data:

C_p	Transportation cost to deploy one module type p in STONS
CM_{ap}	Equals 1 only if module type p can be assigned to an airfield a. From Chapter II, each force module is designed for a specific type of airfield. To prevent an airfield from receiving an unsuitable module, this term should be set to 1 only when module p is suitable for airfield a.
CP_a	Original throughput capacity of airfield a in STONS / day
k	Transportation and setup delay in days. In practice, $k \in \{3,4,5\}$
LD_w	Last day in week w
M_w	Maximum number of modules that can be moved on first day of week w
MCP_p	Throughput capacity of module type p in STONS / day
N_p	Number of module type p available for placement

RQ_{at} Throughput capacity requirement for airfield a on day t in STONS

ρ Weight applied to throughput capacity shortfalls

β Weight applied to transportation cost

Variables:

Y_{apw} Equal to 1 if module p is in place at airfield a on first day of week w and 0 otherwise

X_{apt} Equal to 1 if module p is operational at airfield a on day t and 0 otherwise

Z_{apw} Equal to 1 if module p moved to airfield a on first day of week w and 0 otherwise

S_{at} Throughput capacity shortfall at airfield a on day t

To simplify the presentation, it is assumed that only compatible pairs of (a,p), i.e., ones where $CM_{ap} = 1$, are used when referenced.

Formulation:

Throughput Capacity Expansion Problem with Redeployment (TCEwR)

minimize: $$\beta\sum_a\sum_p\sum_w(C_p * Z_{apw}) + \rho\sum_a\sum_t S_{at} \quad (1)$$

subject to:

$$\sum_p Y_{apw} \leq 1 \qquad \forall\, a,w \quad (2)$$

$$\sum_a Y_{apw} \leq N_p \qquad \forall\, p,w \quad (3)$$

$$Y_{apw} - Y_{ap(w-1)} \leq Z_{apw} \qquad \forall\, a,p,w \qquad (4)$$

$$\sum_a \sum_p Z_{apw} \leq M_w \qquad \forall\, w \qquad (5)$$

$$CP_a + \sum_p (MCP_p * X_{apt}) + S_{at} \geq RQ_{at} \qquad \forall\, a,t \qquad (6)$$

$$X_{apt} \leq Y_{apw} \qquad \forall\, a,p,w \text{ and } LD_{w-1} < t < LD_w \qquad (7)$$

$$X_{apt} \leq 1 - Z_{apw} \qquad \forall\, a,p,w \text{ and } LD_{w-1} < t < LD_w - k \qquad (8)$$

$$X_{apt} \in \{0,1\} \qquad \forall\, a,p,t \qquad (9)$$

$$Y_{apw} \in \{0,1\} \qquad \forall\, a,p,w \qquad (10)$$

$$Z_{apw} \in \{0,1\} \qquad \forall\, a,p,w \qquad (11)$$

$$S_{at} \geq 0 \qquad \forall\, a,t \qquad (12)$$

The objective function (1) consists of two terms. The first term is the weighted transportation cost and the second is the weighted amount of throughput capacity shortfalls. Although each of these objectives can be optimized independently, this thesis optimizes them simultaneously. Together, the weights β and ρ assign a relative importance between transportation cost and shortfalls. The proper values for ρ and β are empirically determined.

Constraint set (2) limits each airfield to having at most one module in place for each week. Constraint set (3) ensures that the number of modules of each type used per week does not exceed the number available. Similar to the technique used in Brown,

Lawphongpanich and Thurman [Ref 7: p.15], constraint set (4) indicates whether a module has been deployed to airfield a on week w. To illustrate, consider the case where module *P1* was in place at airfield *A1* on week 2, but has been redeployed to airfield *A2* on week 3. Constraint (5) generates the following equations:

$$Y_{A1,P1,3} - Y_{A1,P1,2} \leq Z_{A1,P1,3} \tag{13}$$

$$Y_{A2,P1,3} - Y_{A2,P1,2} \leq Z_{A2,P1,3} \tag{14}$$

where $Y_{A1,P1,3} = 0$, $Y_{A1,P1,2} = 1$, $Y_{A2,P1,3} = 1$, and $Y_{A2,P1,2} = 0$. The left hand side of (13) and (14) evaluate to -1 and 1, respectively. The -1 values has no effect on $Z_{A1,P1,3}$ since it is binary. However, at optimality, $Z_{A1,P1,3} = 0$ because of its positive cost coefficient in the objective function. On the other hand, the value of 1 on the left side of (14) forces $Z_{A2,P1,3} = 1$, indicating that *P1* is redeployed to airfield *A2* on week 3. Constraint set (5) sets a limit to the maximum number of modules that can be deployed on the first day of a given week. The first two terms in constraint set (6) represent the original and added, if any, capacities at an airfield a. When these capacities in combination are less than the amount required on day t, S_{at} takes on a positive value equal to the amount of shortfall. Together, constraint sets (7) and (8) determine which days t in week w that a deployed module becomes operational. Constraint set (7) allows a module to be operational at airfield a only when the module is actually deployed there. For example, if $k = 3$ and module *P1* is assigned to airfield *A1* on week 2, then $Y_{A1,P1,2} = 1$ and constraint set (7) will allow $X_{A1,P1,t} = 1$ for $t = 8, 9, \ldots, 14$.

However, if the module *P1* has just been deployed to airfield *A1* on week 2, then $Z_{A1,P1,2} = 1$ and constraint (8) forces $X_{A1,P1,t}$ to be 0 for $t = 8, 9, 10$ to account for the setup delay. Constraints (9), (10) and (11) force *X, Y,* and *Z* to be binary. However, with Y_{apw} being binary and the presence of constraint set (5), the objective function automatically forces Z_{apw} to be either 0 or 1 and constraint set (11) can be replaced with the following:

$$0 \leq Z_{apw} \leq 1$$

Finally, constraint set (12) ensures that capacity shortfalls, S_{at}, are nonnegative.

C. RELATED RESEARCH

The TCE problem with redeployment (TCEwR) presented above is related in structure to the capacity expansion (or capacity planning) problem addressed extensively in operations research literature, see for example Refs 8, 9, 10, 11, 12 and articles cited therein. Specifically, the TCEwR problem contains many similarities to the models presented in works by Luss [Ref 8] and Li and Tirupati [Ref 9]. In Ref 8, Luss addresses a general capacity expansion problem for two facilities and develops a network flow algorithm for solving this problem. In Ref 9, Li and Tirupati examine a single facility, multiproduct capacity expansion problem that considers the choice between two types of expansion, flexible and dedicated technology. The TCEwR problem and the models in Ref 8 and 9 determine a schedule of capacity expansions in an attempt to satisfy known levels of demand for a finite number of discrete time periods. The objective in all three is

to minimize total costs associated with capacity expansion. As in the TCEwR problem, the model in Ref 8 allows capacity shortfalls to occur and penalizes them in the objective function, and in Ref 9, the amount of capacity expansion available for each time period is limited. However, both of these models differ from the TCEwR problem in two ways. First, the *amount* of capacity expansion considered in Refs 8 and 9 is treated as a decision variable and is not limited to discrete levels as in the TCEwR problem, i.e., the four modules' throughput capacities. Second, in Refs 8 and 9, expansion of a facility is permanent whereas capacity expansion in the TCEwR problem is temporary, i.e., a module can be redeployed to different airfields throughout the planning period.

During a preliminary experiment, the TCEwR problem was implemented in the General Algebraic Modeling System or GAMS [Ref 13]. For a sample problem with 8 airfields and a planning horizon of 60 days, the model generates 2208 binary variables, 768 continuous variables and 4853 constraints. Using the IBM RS6000 model 590 and the CPLEX solver [Ref 14], it took over two hours to solve the problem that GAMS generated. Since a more realistic problem contains between 30 and 40 airfields and has a planning horizon of 180 days, the above formulation of the TCEwR problem must be modified to drastically reduce the solution time and make it useful in practice.

It should be noted, however, that the above formulation of the TCE problem is a natural one, for it follows many concepts in the existing literature. In the next chapter, alternate formulations are given. Their main advantage is in the smaller number of variables and constraints which, in turn, lead to a much shorter solution time.

IV. VARIABLE REDUCTION

Recall that the TCE problem in Chapter III contains two sets of variables, one to essentially indicate the availability of additional capacity, X_{apt}, and the other to account for the daily shortfalls, S_{at}. Both sets of variables are not directly associated with the deployment decision. They are mainly *accounting variables,* reporting the consequence of a decision. In combination, X_{apt} and S_{at} report shortfalls for a (optimal) decision to place the modules. To reduce the size of the problem, these two sets of variables should be removed. One method to remove them from the formulation in Chapter III is to enumerate all possible shortfalls for all possible placement decisions. In this manner, there is no need to include variables and constraints to explicitly account for shortfalls.

The first section of this chapter presents a new formulation for the TCE problem with redeployment. The next two sections provide two formulations for the problem where redeployment of modules is not allowed. The formulation of this problem is postponed to these sections in order to take advantage of a more compact approach to the TCE problems. When the redeployment option is not available, there are two possibilities. The first one still assumes that the number of available lift assets are limited. The other places no limit on the number of lift assets used to deliver the modules. Although this second possibility may seem unrealistic, it does have applications. It is possible that the solution to the problem with unlimited lift assets requires acceptable number of aircraft. When the required number of aircraft is not

acceptable, the resulting shortfalls provide a benchmark against which the other module deployment plans can be compared.

A. ALTERNATE TCE PROBLEM WITH REDEPLOYMENT

The following definitions are necessary for the enumeration of all possible shortfalls. Note that these definitions are derived or computed from known data presented in Chapter III.

Definitions:

NP_{aw} = total capacity shortfalls at airfield a during week w if no modules are in place, i.e.,

$$NP_{aw} = \sum_{t=(LD_{w-1}+1)}^{LD_w} \max\{0,\ RQ_{at} - CP_a\} \tag{15}$$

WP_{apw} = total capacity shortfalls eliminated at airfield a if module p is operational at the beginning of the week w, i.e.,

$$WP_{apw} = \sum_{t=(LD_{w-1}+1)}^{LD_w} \min\{\max\{0,\ RQ_{at} - CP_a\},\ MCP_p\} \tag{16}$$

SZ_{apw} = total capacity shortfalls that are *not* eliminated at airfield a when module p does not become operational until the $(k+1)$th day of week, i.e.,

$$SZ_{apw} = \sum_{t=(LD_{w-1}+1)}^{(LD_{w-1}+k)} \min\{\max\{0,\ RQ_{at} - CP_a\},\ MCP_p\} \tag{17}$$

In equation (15), the expression $\max\{0, RQ_{at} - CP_a\}$ calculates the amount of shortfall at airfield a on day t. If the airfield's throughput capacity is greater than or equal

to the required capacity on day t, then the value of this expression is zero, indicating that there is no capacity shortfall. Summing over all days in week w gives the total shortfalls for that week at airfield a.

The summand in equation (16) computes the amount of shortfall eliminated by the module on day t. If the amount of shortfall on day t is less than the module's throughput capacity, i.e., $RQ_{at} - CP_a < MCP_p$, then the "*min*" operation evaluates to zero and there is no shortfall. Conversely, if $RQ_{at} - CP_a > MCP_p$ then the additional module capacity is insufficient and the amount of shortfall eliminated for day t equals MCP_p. The amount of shortfall eliminated by module p during week w, WP_{apw}, is simply the sum of shortfalls eliminated on each day of week w.

By assumption, a module placed at an airfield on day t becomes operational on day $(t + k)$. Thus, WP_{apw} defined in (16) overstates the reduction in shortfall if a module is placed at the beginning of week w. As defined in (17), SZ_{apw} is then the amount of shortfall overstated by WP_{apw} for week w.

Below is a more compact formulation of the TCE problem with redeployment. The decision variables, Y_{apw} and Z_{apw}, are as defined previously.

Formulation:

Throughput Capacity Expansion Problem with Redeployment (New TCEwR)

minimize:

$$\beta \sum_{a} \sum_{p} \sum_{w} \left(C_p * Z_{apw} \right) + \rho \sum_{a} \sum_{w} \left[NP_{aw} - \sum_{p} \left([WP_{apw} * Y_{apw}] - [SZ_{apw} * Z_{apw}] \right) \right] \qquad (18)$$

subject to: Constraint sets (2) to (5), (10) and (11).

As before, the objective function (18) minimizes the weighted sum of transportation costs and total shortfalls. The summand of the second summation contains the following expression,

$$\sum_{p} \left([WP_{apw} * Y_{apw}] - [SZ_{apw} * Z_{apw}] \right)$$

which represents the amount of shortfalls eliminated during week w at airfield a. The first term is the amount of shortfalls eliminated by a module that is operational during the entire week. The other term, involving Z_{apw}, adjusts the amount of shortfall if the module is placed at the airfield at the beginning of week w. This adjustment is necessary since the module is not operational during the first k days of the week. The other term in the second summation, NP_{aw}, is a constant and can be eliminated. However, its presence makes the meaning (total shortfall) of the second summation more evident. As previously explained, Z_{apw} can be treated as a continuous variable between [0,1].

B. TCE PROBLEM WITH LIMITED LIFT ASSETS AND WITHOUT REDEPLOYMENT

Without redeployment, modules can not be moved to other airfields once they are deployed. Therefore, the movement variable Z_{apw} and constraint set (5) become unnecessary and can be eliminated. Although it is possible to restrict module placements to the beginning of each week, it is more general to allow placements on a daily basis. To do so, data and variables with w as one of their subscripts must be replaced with t to indicate daily information or decisions. In particular, M_w becomes M_t which represents the number of modules that can be placed at airfields each day. Recall that M_t is defined in practice by the number and type of aircraft assigned to transporting force modules.

In addition, definitions defined in section A are redefined as follows. Note that SZ_{apw} is unnecessary when redeployment is not allowed.

NP_a = total throughput capacity shortfalls over the entire operation at airfield a if no modules are in place, i.e.,

$$NP_a = \sum_t \max\{0, RQ_{at} - CP_a\} \qquad \forall\, a \qquad (19)$$

WP_{apt} = total amount of shortfalls eliminated by placing module p at airfield a on day t, i.e.,

$$WP_{apt} = \sum_{\hat{t} \geq t+k} \min\{\max\{0, RQ_{a\hat{t}} - CP_a\}, MCP_p\} \qquad \forall\, a,p,t \qquad (20)$$

Similar to (16), the summand of equation (20) computes the amount of shortfall eliminated on a given day if module type p is in place. The index of summation starts on

day $(t + k)$ since modules do not become operational until k days after placement. To account for daily module placement, the original variable Y_{apw} is redefined as follows.

Variables:

Y_{apt} Equals 1 if module p is placed at airfield a on day t and 0 otherwise

Formulation:

TCE Problem with Limited Lift Assets and without Redeployment (TCEwoR/LL)

minimize:

$$\beta\sum_{a}\sum_{p}\sum_{t}(C_p * Y_{apt}) + \rho\sum_{a}\left[NP_a - \sum_{p}\sum_{t}(WP_{apt} * Y_{apt})\right] \tag{21}$$

subject to:

$$\sum_{p}\sum_{t} Y_{apt} \leq 1 \qquad \forall\, a \tag{22}$$

$$\sum_{a}\sum_{t} Y_{apt} \leq N_p \qquad \forall\, p \tag{23}$$

$$\sum_{a}\sum_{p} Y_{apt} \leq M_t \qquad \forall\, t \tag{24}$$

$$Y_{apt} \in \{0,1\} \qquad \forall\, \mathrm{a}, p, t \tag{25}$$

Similar to the TCE problem with redeployment, the objective function (21) minimizes the weighted sum of transportation cost and total shortfalls. Constraint set (22) limits each airfield to having at most one module in place for the entire operation. Constraint set (23) ensures that the number of modules of each type used does not exceed

the number available. Constraint set (24) limits the number of modules that can be placed on any given day. Finally, constraint set (25) forces Y_{apt} to be binary.

C. TCE PROBLEM WITH UNLIMITED LIFT ASSETS AND WITHOUT REDEPLOYMENT

When there is an unlimited number of aircraft, it is logical to place modules at airfields on day 1 since delaying the placement can only increase shortfall. Moreover, doing so further reduces the size of the problem, for the subscript t becomes unnecessary. In fact, total shortfalls and the placement variable, Y_{ap}, can now be redefined as follows.

WP_{ap} = total shortfalls eliminated if module type p is placed at airfield a, i.e.,

$$WP_{ap} = \sum_{t \geq k+1} \min\{\max\{0, RQ_{at} - CP_a\}, MCP_p\} \qquad \forall\, a,p \qquad (26)$$

Variables:

Y_{ap} Equals 1 if module type p is assigned to airfield a

Formulation:

TCE Problem with Unlimited Lift Assets and without Redeployment (TCEwoR/UL)

minimize:

$$\beta \sum_{a} \sum_{p} (C_p * Y_{ap}) + \rho \sum_{a} [NP_a - \sum_{p} (WP_{ap} * Y_{ap})] \qquad (27)$$

subject to:

$$\sum_{p} Y_{ap} \leq 1 \qquad \forall\, a \qquad (28)$$

$$\sum_{a} Y_{ap} \leq N_p \qquad \forall \text{ p} \qquad (29)$$

$$Y_{ap} \in \{0,1\} \qquad \forall \text{ a,p} \qquad (30)$$

The above objective function and constraints are similar to the previous problem.

Although the assumption that modules are placed on day 1 may be logical, it may be desired to delay placement if shortfall is not effected. Movement of cargo and personnel to their destination at the beginning of a military operation is critical. So, more aircraft available during the initial phase is highly desirable. When examined closely, modules do not need to be deployed until k days prior to the first occurrence of shortfalls at airfields. More precisely, define τ_a to be the first occurrence of shortfall at airfield a, i.e., $\tau_a = \min\{t\colon RQ_{at} - CP_a\}$. Then, if $Y^*_{ap} = 1$, i.e., module p is placed at airfield a, the module can be placed on day t^*_a, where $t^*_a = \max\{1, \tau_a - k\}$.

The next chapter presents solutions and applications of the TCE problems discussed above.

V. IMPLEMENTATION AND APPLICATIONS

The formulations discussed in the previous chapter are implemented on a 486/33 MHz personal computer with the General Algebraic Modeling System using the XA solver [Ref 15]. To illustrate the use of these formulations in solving the TCE problem, the first section below presents a sample TCE problem and the solutions obtained via GAMS. The last section demonstrates some applications of these formulations to provide information useful for planning effective airlift operations.

A. SAMPLE PROBLEM

As an illustration, a sample TCE problem was constructed using data from a fictitious airlift operation provided by the USAF's Studies and Analysis Agency, Washington, D.C. [Ref 16]. This data includes (1) all movement requirements for the planning period of 180 days, (2) a listing of the 7 APOEs and 28 APODs to be used in the operation, and (3) their respective throughput capacities. Table 2 shows a summary of the available and required throughput capacities for each airfield in the sample problem. Airfields A1 to A7 denote the seven APOEs and the rest are APODs. When comparing the available and required throughput capacities on a daily basis, there are two instances where the required throughput capacity at airfield A6 exceeds its available capacity by more than ten standard deviations. If these two instances are included as part of the problem data, they will dominate total shortfalls and render the analysis uninteresting. Therefore, the two instances were removed from the problem data.

Airfield	Airfield Type	Available Thru Cap (STONS)	Required Thru Cap (STONS) Mean	Std. Dev.	# of Days Req Cap > Avail Cap
A1	APOE	3465	1045.80	1718.38	5
A2	APOE	1808	166.00	124.45	0
A3	APOE	10848	244.78	568.32	0
A4	APOE	17176	296.33	502.66	0
A5	APOE	4520	2619.64	4317.46	5
A6	APOE	7232	5146.37	5277.96	9
A7	APOE	4520	642.31	1347.04	1
A8	APOD	904	350.35	375.27	3
A9	APOD	3465	516.71	718.43	0
A10	APOD	904	138.93	201.41	0
A11	APOD	1925	121.54	187.19	0
A12	APOD	904	248.64	378.80	1
A13	APOD	7232	1850.59	2580.96	2
A14	APOD	1808	271.60	523.61	1
A15	APOD	904	407.61	563.82	6
A16	APOD	17176	81.64	99.32	0
A17	APOD	5424	123.20	153.63	0
A18	APOD	904	2747.58	2517.77	6
A19	APOD	904	262.67	267.74	0
A20	APOD	6328	394.64	873.82	0
A21	APOD	2712	136.02	143.81	0
A22	APOD	904	240.85	241.79	1
A23	APOD	2712	819.82	620.23	0
A24	APOD	1155	726.00	924.90	1
A25	APOD	904	49.00	0.00	0
A26	APOD	2712	301.53	605.86	0
A27	APOD	904	422.76	415.62	5
A28	APOD	904	193.00	175.36	0
A29	APOD	1808	889.00	832.97	7
A30	APOD	6328	4532.60	6296.10	16
A31	APOD	904	124.50	166.74	0
A32	APOD	904	307.85	336.09	1
A33	APOD	1808	1026.70	1316.50	9
A34	APOD	1808	481.43	506.24	0
A35	APOD	4520	217.70	246.63	0

Table 2: Summary Statistics for Airfield Capacity Requirements

Table 3 lists the module types available in the TCE problem, their throughput capacities, transportation cost and where they can be placed. For each type of module, only two modules are available for placement, i.e., $N_p = 2$ for all p. According to Table 3, any APOD airfield can be designated as a stage, hub or spoke airfield which may be unrealistic. However, more realistic data is not available in an unclassified form and this issue is further addressed in a later section. Finally, the maximum number of modules that can be moved in a week is two, i.e., $M_w = 2$ for all w.

Module Type	Module Name	Throughput Cap. (STONS/ Day)	Possible Placement	Trans. Cost (STONS)
P1	Onload	200	APOE	217
P2	Stage	99	APOE/APOD	962
P3	Hub	500	APOE/APOD	1942
P4	Spoke	60	APOE/APOD	509

Table 3: Module Compatibility

For the sample TCE problem with redeployment, GAMS took less than three minutes to generate 2507 binary variables, 3934 continuous variables and 4142 constraints and the solver, XA, took another 19 seconds to produce an optimal solution. Figure 3 displays the output for the problem in which $\beta = 1$ and $\rho = 7$. The cross-hatched bars represent the weekly locations for each module type. To illustrate, consider module type P3. On week 1 of the sample problem, two P3 modules are placed at airfields A5 and A30. On week 3, the P3 module at airfield A5 is redeployed to airfield A33 where it remains until it is moved to airfield A6 on week 5. Figure 3 also allows for quick verification that no more than two of each module type are deployed at any one time.

Reading down the column for each week shows that no more than two blocks are shaded for each type of module.

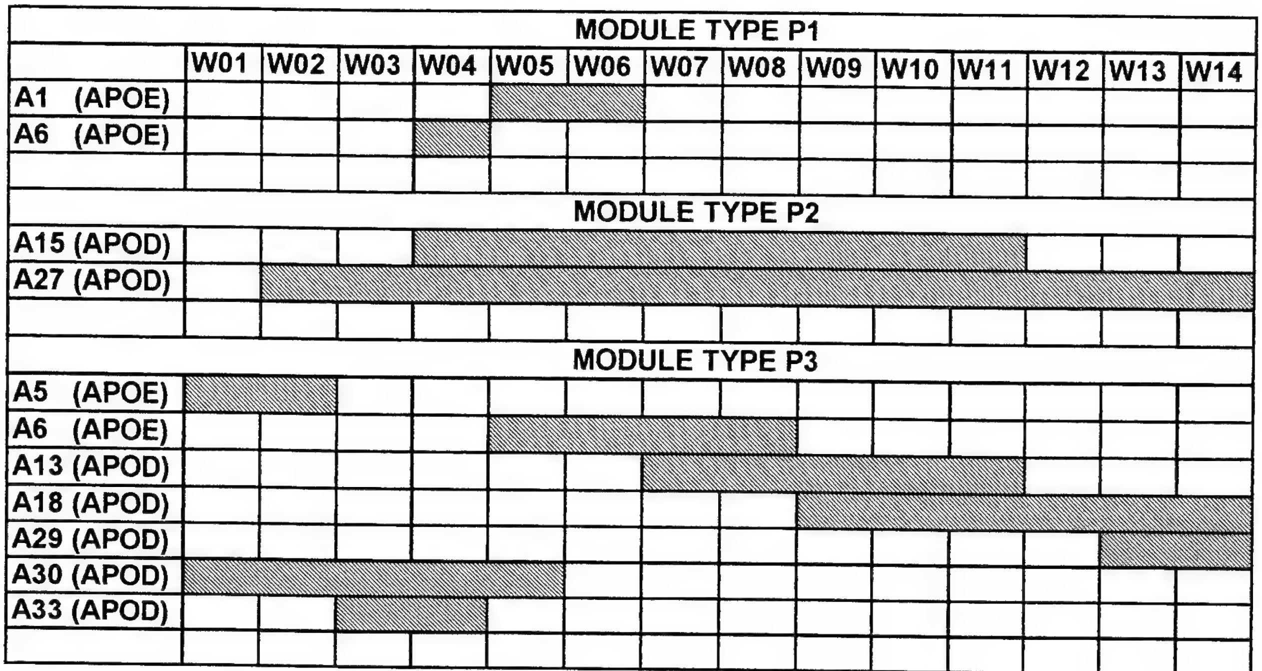

Figure 3: Deployment Schedule for TCE Problem with Redeployment

Although there are four APOEs with shortfalls, only the three with the most shortfalls, i.e., A1, A5 and A6, received modules. In this solution, a P1 module is deployed to airfields A1 and A6. Note that this can be done by deploying two different P1 modules or redeploying one from A6 to A1 on week 5. Since the transportation cost for either case is the same, they are alternate optimal solutions. Also, note that this solution does not place any P4 modules. Computing the cost to benefit ratio, *C/B,* for the four types of modules, where *C* and *B* are the module's transportation cost and throughput capacity, respectively, shows that P4 has a lower cost per unit of throughput capacity than P2. Based on the *C/B* ratios, it should be more attractive to place a P4 module.

However, this solution indicates that a module's throughput capacity is more important than its cost to benefit ratio. This makes sense since shortfalls are weighted more heavily than transportation cost in this sample problem, i.e., $\beta = 1$ and $\rho = 7$.

For comparison, the two TCE problems without redeployment, i.e., TCEwoR/LL and TCEwoR/UL, were solved with $\beta = 1$ and $\rho = 7$. For the TCEwoR/LL problem, the maximum number of modules that can be deployed on any day equals two, i.e., $M_t = 2$. GAMS took approximately 8 minutes to generate 17400 binary variables and 201 constraints in the TCEwoR/LL problem and the solver XA required another 3 seconds to produce an optimal solution. For the TCEwoR/UL problem, GAMS/XA generated 141 binary variables, 41 constraints and found the optimal solution in approximately 25 seconds. For this sample problem, the two TCEwoR problems produced the same optimal solution. In general, an optimal solution for the TCEwoR/UL problem should be no worse than that of the TCEwoR/LL problem since the former is less restrictive. The output for the two TCEwoR problems are listed in Table 4.

AIRFIELD	DEPLOYMENT DATE						
	4	5	8	13	14	18	47
A5 (APOE)	P1						
A6 (APOE)		P1					
A13 (APOD)						P4	
A15 (APOD)							P4
A18 (APOD)				P3			
A27 (APOD)					P2		
A30 (APOD)			P3				
A33 (APOD)	P2						

Table 4: Deployment Plan for TCE Problem without Redeployment

To compare the solutions generated by the TCEwR and TCEwoR problems, Figure 4 displays this deployment schedule shown in a format similar to Figure 3. Without the redeployment option, only eight of the 17 airfields that require expansion can receive modules. Since the P1 modules are only compatible with APOEs, they are deployed to the two APOEs with the most shortfalls, A5 and A6. Of the remaining six airfields that are expanded, this schedule places the modules with the largest throughput capacities at the airfields which have the greatest amount of shortfalls.

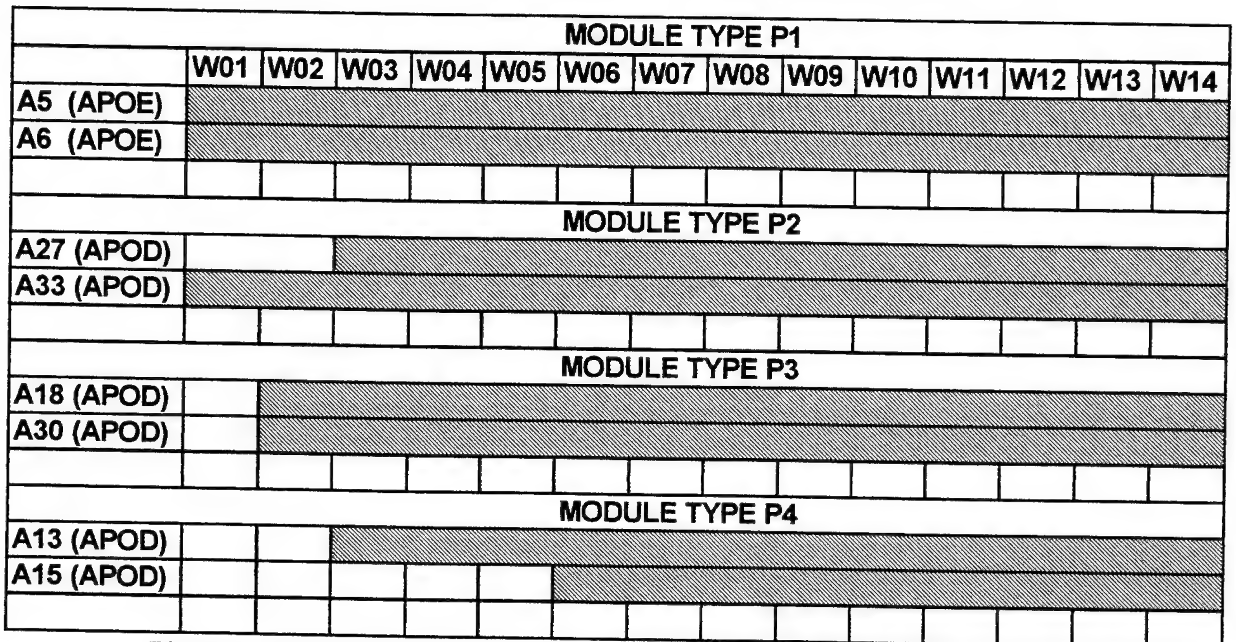

Figure 4: Deployment Schedule for TCE Problem without Redeployment

Tables 5 provides a summary of the optimal solutions obtained by the TCEwR and TCEwoR problems. It is interesting to note that, in this sample TCE problem, redeployment of the modules is of little benefit since it reduces total capacity shortfalls

by only 3.9% more than placement without redeployment, while requiring over twice the amount of airlift assets.

Redeployment	Total Shortfalls (no modules)	Total Shortfalls (with modules)	Percent Decrease	Total Cost (# of C-5s)
With	9171 STONS	6756 STONS	26.40%	140
Without	9171 STONS	7110 STONS	22.50%	64

Table 5: Summary of Optimal Solutions

Besides determining an optimal deployment schedule, the solutions to the TCE problems provide airlift planners with the amount of daily shortfall at each airfield. To illustrate, Figure 5 displays the level of daily shortfall at airfield A15 before and after the deployment of force modules in the TCEwR problem. From the deployment schedule in Figure 3, a P2 module is placed at the airfield on week 4, increasing the airfield's throughput capacity by 99 STONS / day which is insufficient to eliminate shortfalls on days 51, 53, 62 and 74. To eliminate the remaining shortfalls, a different module is required at A15. Being an APOD, the only compatible module with sufficient capacity to eliminate 175 STONS of daily shortfall is P3. So, if an additional P3 is available, shortfalls at A15 can be completely eliminated.

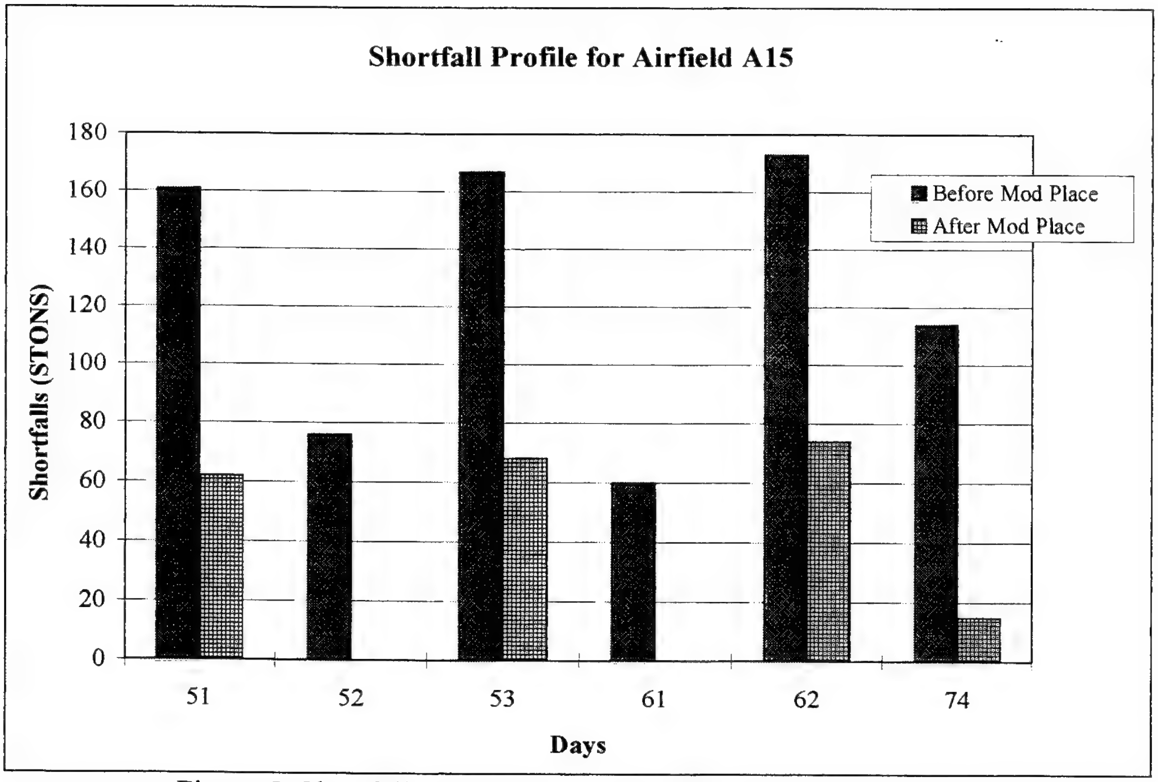

Figure 5: Shortfall Profile Before and After Module Placement

B. APPLICATIONS

To illustrate possible applications of the TCE problems, this section examines three issues of interest. They are: (1) the trade-off between lift asset availability and shortfalls, (2) the benefits of additional force modules and (3) the effect of airfield/module compatibility. The data used to examine these issues are the same as in Section A.

1. Lift Asset Availability and Shortfalls

Recall that there are two parameters, β and ρ, that represent weights assigned to transportation cost and shortfalls, respectively. Figure 6 depicts the resulting total capacity shortfalls from the TCEwR problem with $\beta = 1$ and ρ varied between one and eight. As ρ increases, the total amount of shortfalls decrease as expected. Similarly, Figure 7 graphically displays the relationship between ρ and total transportation cost from the same TCEwR problem. Note that the transportation cost in Figure 7 is expressed as the number of C-5s required to place the modules optimally. It is simply the total transportation cost in STONS divided by a C-5's capacity which is 100 STONS.

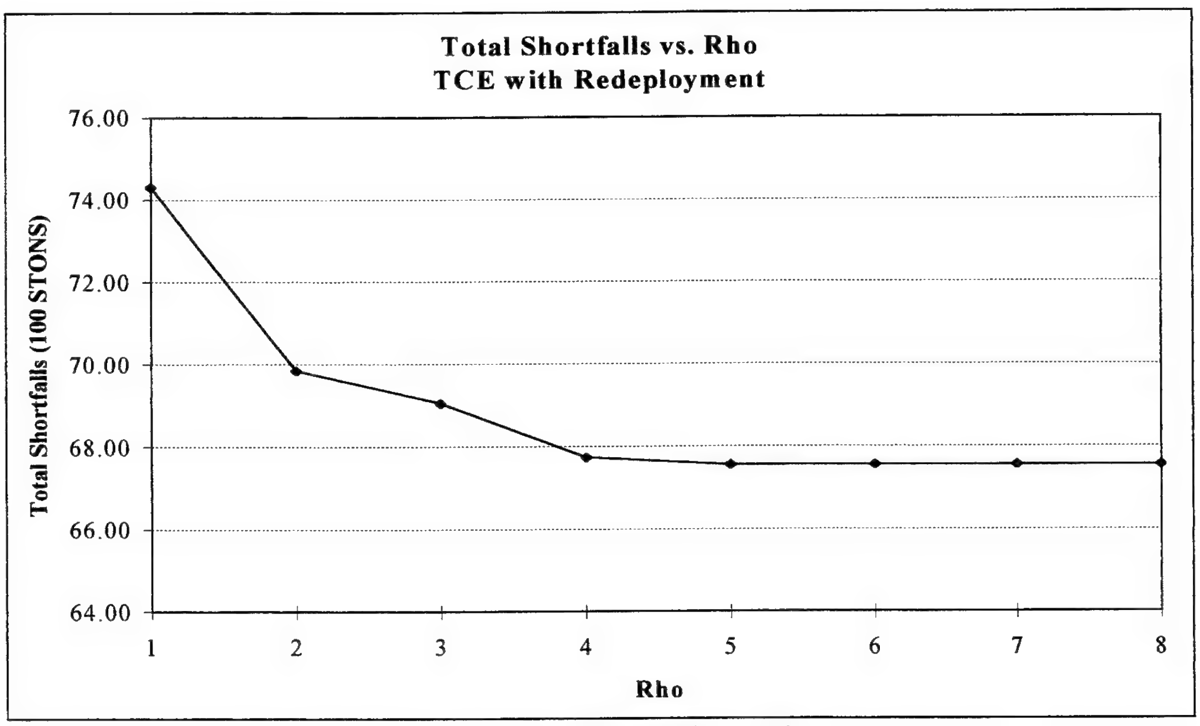

Figure 6: Total Shortfalls vs. Rho

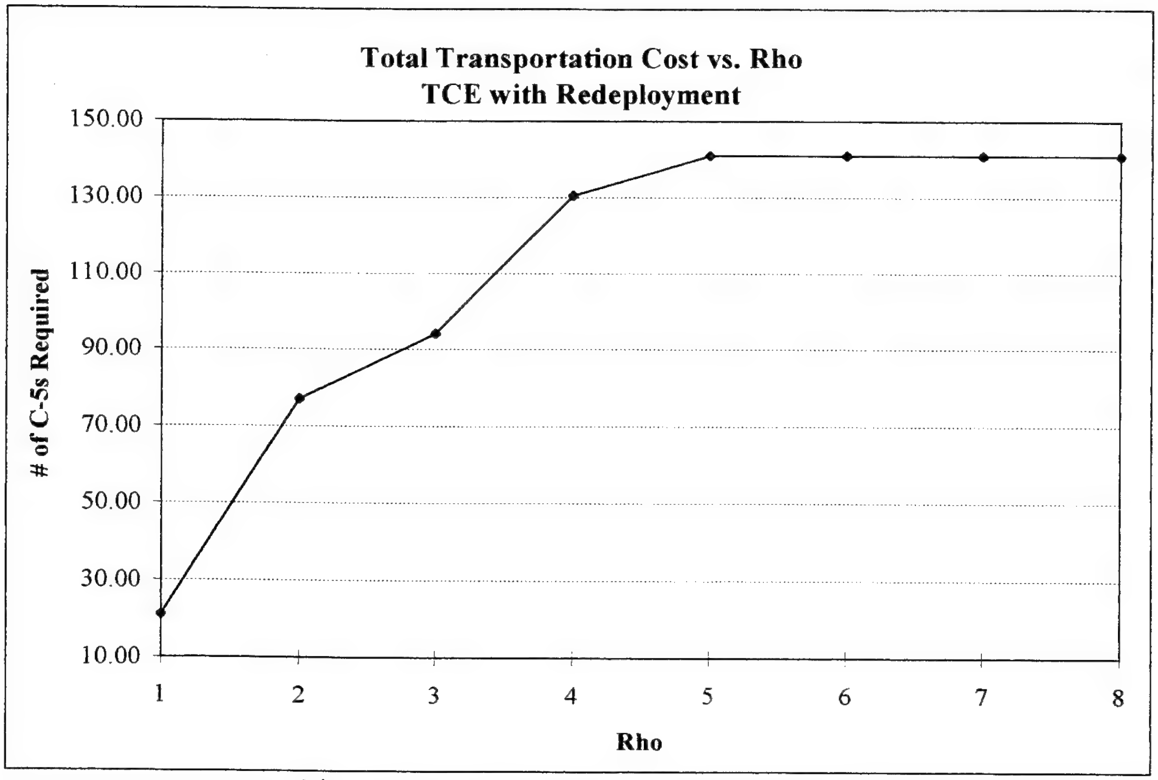

Figure 7: Total Transportation Cost vs. Rho

The light shaded curve in Figure 8 is a different representation of the information in Figures 6 and 7. It is generated by Microsoft Excel [Ref 17] to represent the trend line through the (square) dots representing possible combinations of shortfalls and transportation costs. This trend line is simply a trade-off curve. Using the curve, if there are 55 C-5s available, then shortfalls of nearly 7100 STONS should be expected. On the other hand, if 6900 STONS is the most shortfalls that can be allowed to ensure a successful mission, then approximately 93 C-5s are needed.

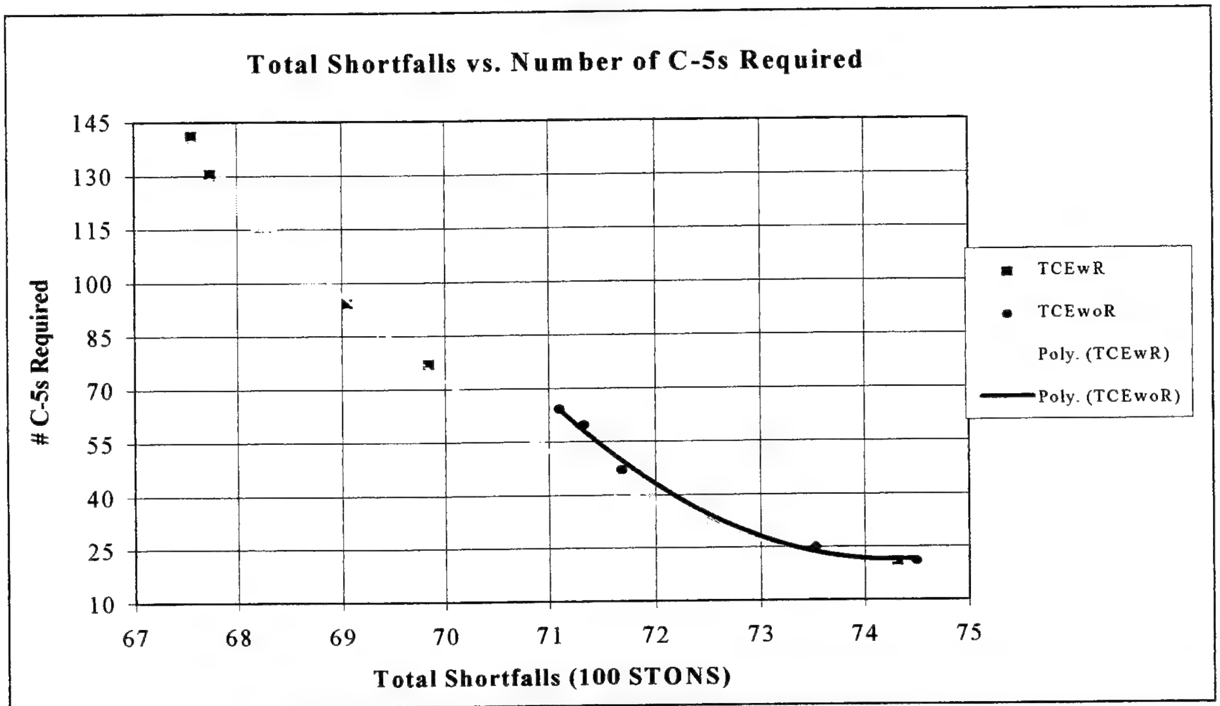

Figure 8: Lift Asset Availability and Total Shortfalls

To compare the with and without redeployment options, the trade-off curve for the TCEwoR problem, i.e., the dark shaded curve, is also displayed in Figure 8. Intuitively, the fact that the trade-off curve for the no redeployment option lies above the one with redeployment makes sense. For the same amount of shortfalls, the one with the redeployment option should require no more C-5s than the one without, for the former is less restrictive. At 7200 STONS of shortfalls, approximately 38 and 45 C-5s are required under the with and without redeployment options, respectively. As shortfalls increase, the number of C-5s required by the two options are the same. The point at which the two trade-off curves coincide varies depending on the data. Our data suggest that, if 7300

STONS of shortfalls are acceptable, approximately 28 C-5s are needed regardless of the option.

2. Additional Sets of Force Modules

AMC identifies a set consisting of one module of each type as a *package*. In the sample problem in Section A, two packages are available for deployment. By varying the number of available packages and resolving the TCE problem, the amount of shortfall reduction obtained can be examined to determine if justification exists for procuring additional packages. Figure 9 summarizes the results of varying the available number of packages in the TCEwR problem with $\beta = 1$ and $\rho = 7$. Note that there is at most a 2% reduction in shortfalls if more than two packages are available. Based on this sample problem data, there is no justification for further procurement of packages.

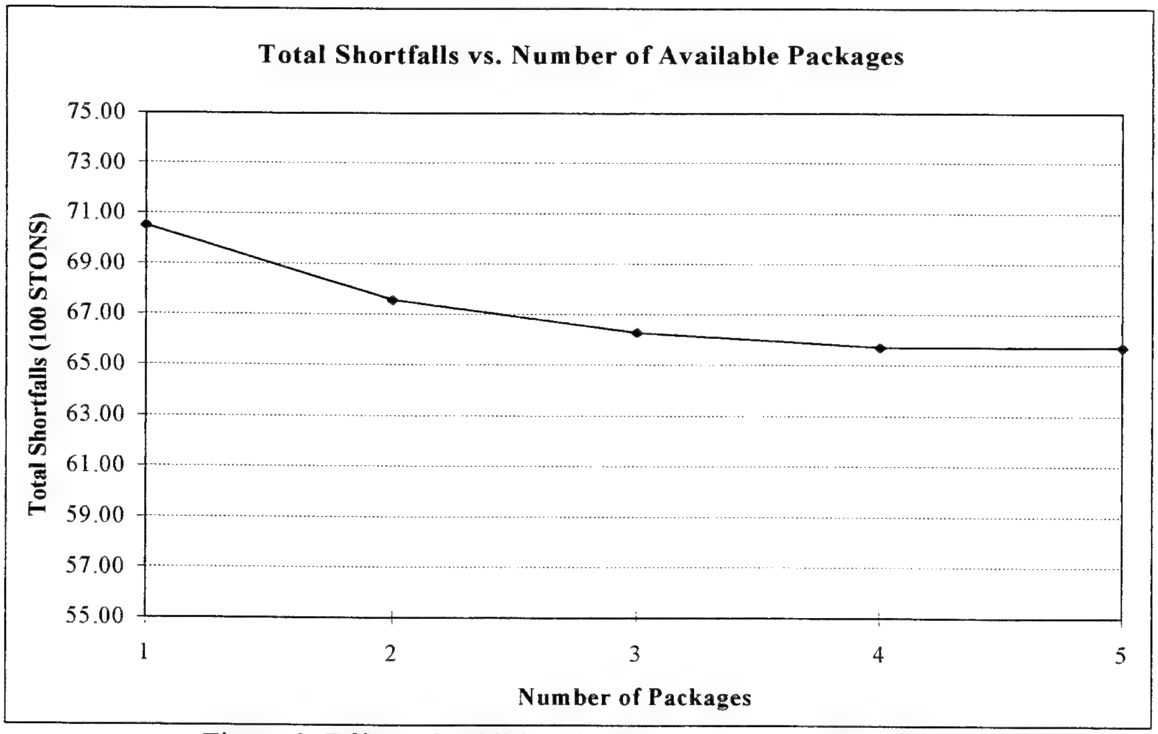

Figure 9: Effect of Additional Packages on Total Shortfalls

3. Compatibility of Module Types and Airfields

In the absence of more detailed data, an assumption for airfield/module compatibility made earlier in this chapter allows all airfields to receive Hub, Spoke or Stage modules. To examine the effect of this assumption, the TCEwR problem is resolved with different degree or percent compatibility between airfields and modules. At the desired degree or percent compatibility, denoted as q, pairs of compatible modules and airfields are randomly generated. In particular, if r is a uniform random variable between 0 and 1, then a given airfield-module pair, (a,p), is compatible, i.e., $CM_{ap} = 1$, when $r \leq q$. This process is repeated for all possible pairs (a,p).

Using the same data as in Section A with $\beta = 1$ and $\rho = 7$, Figure 10 displays how shortfalls vary using different percent compatibility. Clearly, the effect on the shortfalls is negligible beyond 50%. Moreover, the difference in shortfalls at 25% and 50% compatibility is only 3%. These results suggest that the results in Section A are valid if the true compatibility is at least 50%.

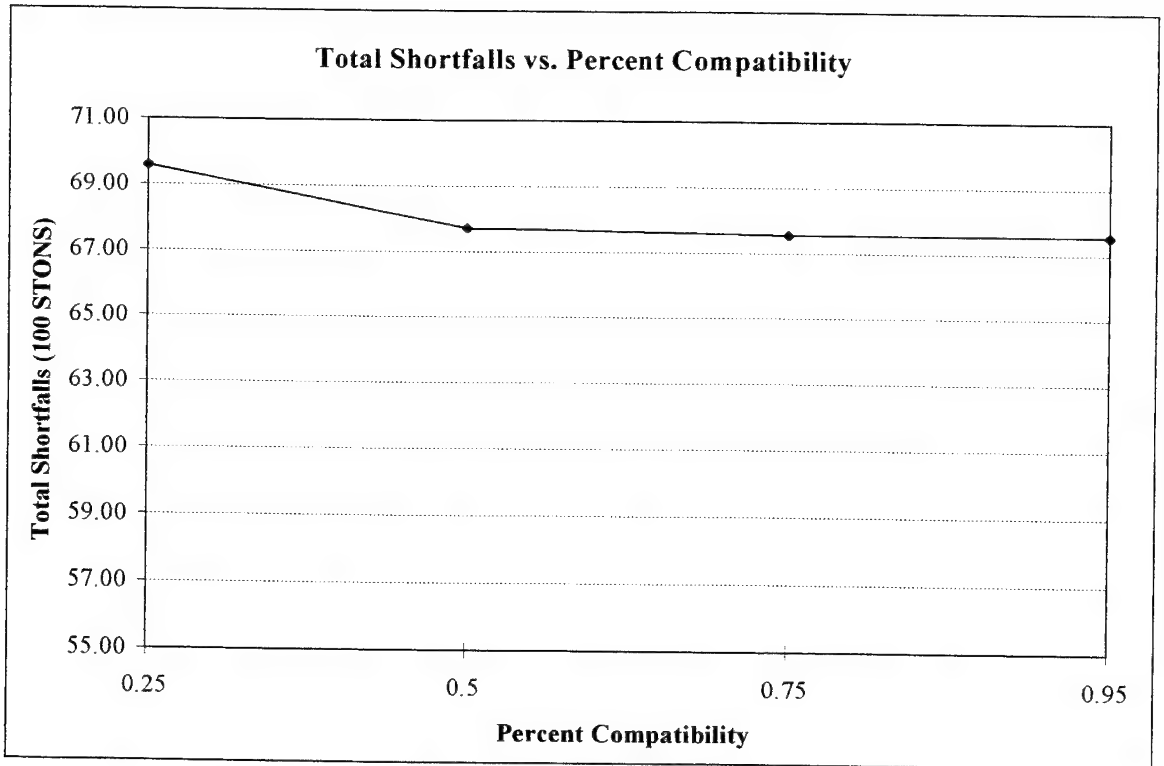

Figure 10: Shortfalls and Airfield/Module Compatibility

VI. CONCLUSIONS

Realignment of the US military's force structure has reduced the number of overseas airfields available for use in airlift operations. Without adequate number of airfields that have sufficient capacity, troops and materiel can not be delivered to the right place at the right time. To effectively support a wide range of contingency operations, the USAF's Air Mobility Command (AMC) must have the ability to rapidly expand the capacities of the remaining airfields. With the development of the Global Reach Laydown Package (GRLP) concept, AMC can selectively deploy mobile infrastructure, i.e., GRLP force modules, to increase airfield throughput capacity.

The goal of this thesis is to aid airlift planners in determining the most effective placement of these modules to support the required cargo movement in an airlift operation. In particular, the decision of where and when to place these modules is formulated as integer programming problems, also known as Throughput Capacity Expansion (TCE) problems. There are two options in placing the modules. One allows modules to be redeployed to different airfields after their initial placement and the other does not. As an objective, problems under both options minimize the weighted sum of the total amount of capacity shortfalls and the transportation cost associated with deploying force modules.

When implemented in GAMS, solutions to the TCE problems specify schedules for deploying/redeploying force modules at various airfields. Moreover, as an aid in

decision making, these solutions can be analyzed and provide useful information. Based on the sample data, the analysis shows that (i) the trade-off between availability of lift assets and shortfalls can be quantified, (ii) the marginal decrease in shortfalls from having three or more packages of force modules is negligible, and (iii) shortfall is unaffected by airfield/module compatibility if more than 50% of the airfield-module pairs are compatible.

This thesis suggests the following area for future research:

1. This thesis examined capacity expansion for APOEs and APODs only. However, other studies (see, e.g., Ref 3) indicate that limited MOG values at intermediate, i.e., enroute, airfields can create "bottlenecks" and cause late delivery of cargo and passengers. The effect of placing these force modules at enroute airfields needs to be examined.
2. The Air Force has indicated that new modules types are under consideration for development [Ref 18]. These TCE problems can be used as a tool to evaluate the benefits of any new module types.

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